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Visible Light Hazard at the NSLS VUV and X-ray Rings

1. Introduction

Alignment of the optical components of beamlines on the VUV and X-ray rings is often best accomplished by using the visible portion of the bending magnet synchrotron radiation spectrum. To do this, light is brought through a glass (typically Corning type 7056 borosilicate glass) window that transmits wavelengths from 280 to 3000nm. Fused silica or sapphire windows may also be in use and transmit farther into the UV range than borosilicate glass. Note that the only NSLS insertion device that produces output in the visible portion of the electromagnetic spectrum is U13U undulator. The visible light intensity from U13U is much higher than that from bending magnets, and must not be brought outside the U13 beamline vacuum chambers without special provisions. No visible light is produced by the U5U, X1, and X13 MGU undulators. This document presents a calculation of the hazard that the visible emission from the NSLS VUV and X-ray ring bending magnets presents to the human eye, following the guidelines published by the American Conference of Governmental and Industrial Hygienists (ACGIH) in their 2001 Threshold Limit Values (TLV) document.

NOTE

Any alignment work involving visible light will be planned and controlled through the use of an NSLS Safety Approval Form.

According to the ACGIH publication, the light hazards which need to be considered fall into three types, depending on damage mechanism, which correlates somewhat with spectral range: retinal thermal injury from a visible (and near infrared) light source (385-1400 nm); retinal photochemical injury from chronic blue-light (305-700 nm) exposure; and infrared radiation (770-3000 nm), which is further subdivided into (a) protection of the cornea and lens, and (b) protection of the retina. These regions are considered in order below.

2. Retinal thermal injury from a visible (and near infrared) source (385-1400 nm) [reference ACGIH p. 151]

The recommended TLV for this spectral region is defined by the following inequality:

$$\sum_{385nm}^{1400nm} L(\lambda)R(\lambda)\Delta\lambda \leq \frac{5\frac{W \cdot rad \cdot \sec^{0.25}}{cm^2 \cdot sr}}{\alpha \cdot t^{0.25}} \qquad (1)$$

where L(λ) is the spectral radiance of the source in W/(cm^2 sr nm), R(λ) is the retinal thermal hazard function, t is the viewing duration in seconds for a continuous wave (CW) source (the synchrotron radiation from the NSLS storage rings is CW on the scale of physiological effects on the human eye), and α is the angular subtense of the source in radians (the angular size of the source as seen from the viewing location). This TLV assumes a 7mm diameter, dark-adapted pupil and may be modified for daylight conditions. However, in the absence of guidance for daylight conditions, we will conservatively use the dark-adapted value. The vertical angular dependence of bending magnet synchrotron radiation is confined to a few milliradians above and below the orbital plane, so the peak radiance (orbital plane value) for L(λ) will be used in Eq. 1. The summation on the left-hand side of Eq. (1) over the 385-1400 nm wavelength range is $8.30 \times 10^4 \frac{W}{cm^2 \cdot sr}$. For the right-hand side of Eq. 1, we need values for the viewing duration time t and the angular subtense of the source α. For t, we assume only an accidental exposure time given by the human blink response time of 0.25 seconds. For the angular subtense, we must consider two cases: (a) direct viewing of the source, with no intervening optical elements (other than the visible-transmissive glass viewport) and (b) transmission through an optical system before emerging from a visible-transmissive glass viewport. In case (a), no viewport on the NSLS storage rings allowing line-of-sight viewing of the source is closer than 2000mm from the source. Since the beam size in the NSLS storage rings is ~1mm, an angular subtense value of 1mm/2000mm = 0.5mrad is used. In case (b), the optical system losses in the IR/visible range must be conservatively assumed to be negligible. Furthermore, it must be assumed that the optics could bring the emitted beam to a focus at a point downstream of the glass viewport, i.e. where a human eye could be located. In this latter case, the angular subtense alpha may become large, since the distance from "source" (i.e. the focused source) approaches zero. In case (a), the right-hand side of Eq. 1 is the TLV for 1 Ampere circulating VUV ring beam current:

$$\frac{5\frac{W \cdot rad \cdot \sec^{0.25}}{cm^2 \cdot sr}}{0.0005 rad \cdot (0.25 \sec)^{0.25}} = 1.41 \times 10^4 \frac{W}{cm^2 \cdot sr}$$

The radiance of 8.30 x 10^4 is 6 times higher than the TLV of 1.41 x 10^4.

3. Retinal photochemical injury from chronic blue-light (305-700 nm wavelengths) [reference ACGIH p. 152]

3a. To protect against retinal photochemical injury from chronic blue-light (305-700 nm wavelengths) exposure, the integrated spectral radiance of a light source weighted against the blue-light hazard function B(λ) should not exceed $\frac{100}{t}\frac{W}{cm^2 \cdot sr}$ for viewing (exposure) times t less than 10^4 seconds. The blue-light-hazard-weighted spectral radiance of the NSLS VUV ring integrated from 305-700nm is $7231\frac{W}{cm^2 \cdot sr}$, so that the maximum permissible exposure time to the human eye is 100/7231 = 14msec, which is ~18 times shorter than the human blink reflex time of 0.25sec.

3b. The TLV guidelines also include a relaxed limit for sources that subtend an angle less than 11mrad, which applies to a good fraction of the beamlines on the NSLS storage rings. This relaxed guideline holds that the integrated spectral irradiance (power per unit area illuminated, independent of angular dependence) of a light source weighted against the blue-light hazard function B(λ) should not exceed $10\frac{mW}{cm^2}$ for viewing (exposure) times less than 10^4 seconds. For the direct illumination (no optical elements) case, the closest distance from the source is assumed to be 200cm, so a 1cm-size illuminated spot subtends 5mrad at the source. Therefore, a conservative overestimate of the integrated spectral irradiance is given by assuming that the central (i.e. in the orbital plane) intensity of the synchrotron radiation emission is uniform over 5mrad × 5mrad solid angle (this is a good approximation horizontally, but an overestimate vertically). The central intensity of a VUV ring bending magnet at 1Amp circulating current, multiplied by the blue-light-hazard function, and integrated over the 305-700nm wavelength range is, in power units, $4.83 \times 10^{-5}\frac{W}{mrad^2}$. At a distance of 200cm from the source, this corresponds to a power density of $4.83 \times 10^{-5}\frac{W}{mrad^2} \cdot \left(\frac{5mrad}{cm}\right)^2 = 1.21\frac{mW}{cm^2}$, a value that is safely less than the TLV of $10\frac{mW}{cm^2}$.

3c. The blue-light hazard function used above assumes that the person has not had his/her crystalline lens removed, as by cataract surgery, for example. In that case the blue-light hazard function is modified to emphasize the wavelengths below blue (. 400nm). The synchrotron brightness increases as the wavelength decreases in the 305-700 nm range, so the blue-light hazard in the lens-removed case is considerably worse than the values given above which assume the presence of the lens. It is recommended that workers without lenses (cataract surgery patients) be excluded from any situations that could involve visible alignment beams from the NSLS storage rings.

4. Infrared radiation (770-3000 nm), which is further subdivided into (4a) protection of the cornea and lens, and (4b) protection of the retina [reference ACGIH p. 154]

4a. To avoid thermal injury of the cornea and possible delayed effects upon the lens of the eye, infrared radiation (770-3000 nm wavelengths) should satisfy the following inequality:

$$\sum_{770nm}^{3000nm} E(\lambda)\Delta\lambda \le \frac{1.8\frac{W \cdot \sec^{0.75}}{cm^2}}{t^{0.75}} \qquad (2)$$

for times t < 1000s, where E(λ) is the spectral irradiance. Since the infrared synchrotron radiation from the NSLS storage rings is always accompanied by the bright visible portion of the spectrum, we can assume, as above, that t is defined by the human blink reflex time = 0.25sec.

Thus, the right-hand side of Eq. 2 becomes $\dfrac{1.8\dfrac{W\cdot\sec^{0.75}}{cm^2}}{(0.25\sec)^{0.75}} = 5.1\dfrac{W}{cm^2}$ which is the TLV. The central (i.e. in the orbital plane) intensity of a VUV bending magnet at 1Amp circulating current integrated over the 770-3000nm wavelength range is, in power units, $6.67\times10^{-5}\dfrac{W}{mrad^2}$. For the direct illumination (no optical elements) case, the closest distance from the source is assumed to be 2000mm (i.e. 0.2cm illuminated length per mrad), so the integrated spectral irradiance is $6.67\times10^{-5}\dfrac{W}{mrad^2}\Big/\left(\dfrac{0.2cm}{mrad}\right)^2 = \dfrac{1.67mW}{cm^2}$. This value is very much lower than the right-hand-side value of 5.1 W/cm^2, which is the TLV.

4b. To protect the retina for exposure periods less than 10 seconds (again, we assume a blink reflex of 0.25 sec since the synchrotron radiation beam has a strong visible component), we can use Eq. 1 where the summation is over the 770-1400nm wavelength range. The left-hand-side of Eq. 1, summed over the 770-1400nm wavelength range, is $2496\dfrac{W}{cm^2\cdot sr}$ for 1 Ampere circulating beam current in the NSLS VUV ring. As discussed in Section 1 above, the right-hand-side of Eq. 1 is the TLV of $1.41\times10^4\dfrac{W}{cm^2\cdot sr}$ for 0.25sec exposure time and a closest distance from source to eye of 2000mm. Thus, the infrared output of the VUV ring is considerably less than the TLV for this case.

We also need to consider a portion of the ultraviolet region of the electromagnetic spectrum. The ACGIH publication divides the ultraviolet region into two regions, one being the entire range from 180-400nm and the other specifically for the UV-A region from 315-400nm. Below, we consider both ranges.

5. Ultraviolet radiation (180-400nm)[reference ACGIH p. 155]

For exposure to the eye, the TLV is defined by the inequality:

$$t\cdot\sum_{180nm}^{400nm}E(\lambda)S(\lambda)\Delta\lambda \le 3\frac{mJ}{cm^2} \qquad (3)$$

where E(λ) is the spectral irradiance of the source in $\frac{W}{cm^2 \cdot nm}$, S(λ) is the relative spectral effectiveness, which peaks (with a value of 1.0) at 270nm (unitless), and t is the exposure time in seconds. The exposure time t is assumed to be given by the human eye reflex time, 0.25 seconds, since the bright visible beam accompanies the synchrotron bending magnet emission. The integral from 180-400nm in the left-hand-side of Eq. 3 is $3.33\frac{mW}{cm^2}$, where we have assumed the case of direct illumination (no optical elements) in which the closest distance from the source is assumed to be 2000mm (i.e. 0.2cm illuminated length per mrad). Multiplying by t = 0.25sec, the left-hand-side of Eq. 3 becomes $0.83\frac{mJ}{cm^2}$, which is safely less than the TLV of $3\frac{mJ}{cm^2}$.

6. UV-A spectral region (315-400nm wavelengths) [reference ACGIH p. 157]

For exposure periods less than 1000 seconds, the TLV is a radiant exposure of $1.0\frac{J}{cm^2}$. The differences between this requirement and that above in section 5 are the smaller wavelength range and the absence of a spectral effectiveness function S(λ). The wavelength-integrated irradiance from a VUV bending magnet over the 315-400nm range is $2.74\frac{mW}{cm^2}$ at 2000mm from the source. For an exposure time of 0.25 seconds, this corresponds to a radiant exposure of $0.69\frac{mJ}{cm^2}$, which is three orders of magnitude less than the TLV of 1.0 J/cm^2.

7. Conclusions

The synchrotron radiation emission from an NSLS VUV ring bending magnet with a circulating current of 1 Ampere is lower than the established TLV's in the infrared (770-3000nm) and ultraviolet (180-400nm) regions, but higher than the TLV's in the visible and near-infrared range (385-770nm).

See Table 1 and rest of text below.

Table 1: TLV and Synchrotron Radiation Emission at 1 Ampere (unfocused) and at 0.25 sec exposure time

Wavelength Range	TLV (ACGIH)	NSLS VUV (Calculated, 1Amp)	NSLS X-ray (Calculated, 0.32Amp)
(2)385-1400nm (visible-near IR)	$1.41\times10^4 \frac{W}{cm^2\cdot sr}$	$8.30\times10^4 \frac{W}{cm^2\cdot sr}$	$4.27\times10^5 \frac{W}{cm^2\cdot sr}$
(3a)305-700nm (blue-light)	$400\frac{W}{cm^2\cdot sr}$	$7231\frac{W}{cm^2\cdot sr}$	$3.74\times10^4 \frac{W}{cm^2\cdot sr}$
(3b)305-700nm (blue-light, relaxed requirement for ≤11mrad source)	$10\frac{mW}{cm^2}$	$1.21\frac{mW}{cm^2}$	$0.91\frac{mW}{cm^2}$
(4a)770-3000nm (IR-cornea & lens)	$5.1\frac{W}{cm^2}$	$1.67\frac{mW}{cm^2}$	$1.25\frac{mW}{cm^2}$
(4b)770-1400nm (IR-retina)	$1.41\times10^4 \frac{W}{cm^2\cdot sr}$	$2496\frac{W}{cm^2\cdot sr}$	$1.18\times10^4 \frac{W}{cm^2\cdot sr}$
(5)180 400nm (UV)	$3\frac{mJ}{cm^2}$	$0.83\frac{mJ}{cm^2}$	$0.63\frac{mJ}{cm^2}$
(6)315-400nm (UV-A)	$1.0\frac{J}{cm^2}$	$0.69\frac{mJ}{cm^2}$	$0.52\frac{mJ}{cm^2}$

Important Note:
In all of the above wavelength ranges, however, the possibility exists that the beam emerging from a glass viewport onto the experimental floor (for alignment purposes, for example) has been focused by optical elements in the beamline. In these cases, one cannot state in general whether or not the power density of such a focused beam is greater or less than the TLV in any of these wavelength ranges. Also see "case (b)" in Section 2 above for further information.

As a guideline, the total power emitted in the entire 180-3000nm wavelength IR/visible/UV range per horizontal mrad from an NSLS VUV bending magnet is 7.53mW for 1 Ampere circulating current. Linear scaling of the horizontal angular extent determines an upper bound on the total power emitted by a specific beamline. For example, many of the soft X-ray beamlines accept ~15mrad horizontal, so the total IR/visible/UV power for these beamlines is ≤113mW. The IR microscopy beamlines (U2A/B, U10A/B) collect 45mrad horizontally, corresponding to 339mW, and the large-collection far-infrared beamlines (U4IR, U12IR) collect 100mrad, corresponding to 753mW. The corresponding power per horizontal mrad for the NSLS X-ray ring is 3.78mW for 0.32 Ampere circulating current. The largest horizontal angular extent for X-ray beamlines is 18mrad, so the maximum total IR/visible/UV power for the NSLS X-ray beamlines is 68.1mW.

8. Safety Issues

➔Hazard to the Human Eye
Visible light emitted by bending magnet and insertion device ports on the NSLS storage rings shall be treated as hazardous to the human eye.

➔Requirements for Bringing Visible Light onto the Floor
Bringing direct or reflected visible light outside of the beamline or end station vacuum onto the floor (e.g. for alignment) shall be planned and controlled through the use of an NSLS Safety Approval Form (SAF). Controls shall consist of, at a minimum:

- An approved SAF for this experiment
- The alignment area shall be enclosed by yellow/black caution tape and postings (black lettering on yellow background) saying: **CAUTION - Visible Light Hazard**
- Only those persons listed on the SAF shall be allowed within the taped area
- A backstop shall be provided for the visible light beam
- No unattended operations shall be allowed (no Pink Cards)
- Any configuration changes shall first be reviewed and approved by the Experiment Review Coordinator before the experiment may proceed

➔Cataract Surgery Patients
Workers with a missing crystalline lens of the eye (cataract surgery patients) are excluded from any situations that could involve visible alignment beams from the NSLS storage rings.

➔Covering Beam View Ports
All beam view ports capable of transmitting the direct or reflected visible portion of the beam shall normally be covered with a visibly opaque material (red plastic, protective end caps are useful). “Normally” shall be interpreted to mean as often as practical dependent on experimental requirements.
Covers shall bear the warning: **CAUTION - Visible Light Hazard - Do Not Stare Into Beam**
Unattended zero order visible light emissions are not allowed; view ports shall be covered in these cases.
When an end-station is not in use, all its view ports shall be covered.
View ports shall be covered at the end of an experiment.

➔Beamline Safety Checklists
Beamline Safety Checklists should include a check box to ensure that all view port covers are in place at the time the beamline is enabled.

➔Training
Visible light hazard information and cautions shall be included in BLOSA and facility specific training.

9. Reference

ACGIH. 2001 TLVs and BEIs: Threshold Limit Values for Chemical Substances and Physical Agents & Biological Exposure Indices. American Conference of Governmental Industrial Hygienists, Cincinnati, OH. 2001.